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Accuracy of implant placement based on pre-surgical planning of three-dimensional cone-beam images: a pilot study

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Abstract

Aim: To evaluate the precision of transfer of a computer-based three-dimensional (3D) planning, using re-formatted cone-beam images, for oral implant placement in partially edentulous jaws.

Material and Methods: Four formalin-fixed cadaver jaws were imaged in a 3D Accuitomo FPD® cone-beam computed tomography (CT). Data were used to produce an accurate implant planning with a transfer to surgery by means of stereolithographic drill guides. Pre-operative cone-beam CT images were subsequently matched with post-operative ones to calculate the deviation between planned and installed implants.

Results: Placed implants (length: 10–15 mm) showed an average angular deviation of 2° (SD: 0.8, range: 0.7–4.0°) as compared with the planning, while the mean linear deviation was 1.1 mm (SD: 0.7 mm, range 0.3–2.3 mm) at the hex and 2.0 mm (SD: 0.7 mm, range 0.7–2.4 mm) at the tip.

Conclusions: Cone-beam images could be used for implant planning, taking into account a maximal 4° angular and 2.4 mm linear deviation at the apical tip.

Key words: computer-assisted surgery; computed tomography; dental implant; edentulism; ex vivo; jaw bone; stereolithography; surgical template; three-dimensional imaging

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Although osseointegration of oral implants is a predictable consequence of surgical placement, a pre-operative assessment of the bone volume and quality may allow to better predict a successful outcome of implant placement (Jacobs & van Steenberghe 1998). Clinicians should also be aware of the anatomical structures that could be a risk during surgery (BouSerhal et al. 2002, Mraiwa et al. 2003). Vulnerable structures such as mandibular canals and the symphyseal region with its concavities can compromise treatment outcome (Gahleitner et al. 2001, Mraiwa et al. 2003, Quirynen et al. 2003, Liang et al. 2004). Besides, prosthodontic expectations encourage the surgeon to gain precision in planning and positioning of implants.

It is well known that three-dimensional (3D) computed tomography (CT) scan-based pictures allow for a more reliable planning than when only 2D data are available (Jacobs et al. 1999). When pre-operative radiographic images are available, interactive computer software imaging can be used to expand the indications for oral implant-based treatments. The Procera® software is a 3D image-based environment for pre-operative planning purposes (Verstreken et al. 1996, van Steenberghe et al. 2002, 2005), where implants can be planned according to anatomy and prosthetic demands. Promising results were even found in edentulous patients, in whom a pre-surgical treatment planning, pre-fabrication of a final fixed prosthesis and an immediate loading were performed (van Steenberghe et al. 2004). In vivo and ex vivo results revealed a good accuracy of this procedure (van Steenberghe et al. 2002, 2003).

Conflict of interest and source of funding statement

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Recent studies assert that the use of CT in dentomaxillofacial areas is hampered by its high-radiation dose, low spatial resolution in the axial direction, high cost, bulkiness and metal streak artefacts that can occur in the presence of metallic dental restorations (Sukovic 2003). Especially in partial edentulism, when limited areas are to be treated the use of a classical spiral CT can be questioned (BouSerhal et al. 2000, Tyndall & Brooks 2000, Harris et al. 2002).

The recent introduction of volumetric tomography in oral health care may overcome these limitations (Mozzo et al. 1998, Araki et al. 2004), yielding high-quality 3D image data sets at a reasonably low dose (Loubele et al. 2006, for a review, see Guerrero et al. 2006, Scarfe et al. 2006). Especially the development of a flat-panel detector system with a high frame-acquisition rate has improved image quality (Baba et al. 2002, Baba et al. 2004). So far, there are no ex vivo studies available validating the use of cone-beam CT for 3D image-based planning and transfer of oral implant placement using stereolithographic templates in partial edentulism.

This study aimed to find out whether a cone-beam CT scan could be applied for a reliable and predictable 3D computer-based planning and transfer of oral implant placement in partial edentulism. The accuracy of the transfer was evaluated on ex vivo jaws by matching pre- and post-surgerical images of the respective jaw bones.

Material and Methods

Selection and preparation of the ex vivo specimens

Four formalin-fixed cadaver jaws (one upper jaw and three lower jaws) were used for the present investigation. These bone specimens were derived from patients who had donated their bodies for research or teaching purposes at the department of anatomy of the Catholic University Leuven (Fig. 1).

For the formalized cadaver specimens, silicone impressions (Impregum®, 3M Espe AG; Seefeld, Germany) were made to make diagnostic plaster casts (Ultradent, Schouten Groep, Mijnsheerenland, the Netherlands). The radiographic template, mimicking the teeth to be replaced, was adapted to the occlusal plane of the neighbouring teeth. The latter was manufactured by the dental technician in such a way that it touched the gingiva. These radiographic templates were constructed using methacrylate resin (Palapress vario®, Heraeus-Kulzer, Wehrheim, Germany). At each edentulous site of the radiographic guide, six gutta markers were inserted. The gutta-percha points were placed at different levels in relation to the occlusal plane. This was accomplished using a warm gutta-percha injection technique (Obtura II®, Obtura Corporation, Fenton, MO, USA). The appliance was set at 200°C and the needle was placed into prepared round holes with a standard diameter of a 1 mm round bur. A plugger (RCPGL 1®, Hu-Friedy, Chicago, IL, USA) was used to compact firmly the mass of gutta-percha at the orifice.

This set-up allowed simulation of in vivo scanning conditions and export this image data set for a further planning using the Oralim® (Medicim, St. Niklaas, Belgium)/Procera® (Nobel Biocare AB, Göteborg, Sweden) software and transfer of the planning to the surgical field by drilling templates on formalized cadavers.

Fig. 1. Four formalin fixed cadavers. A stereolithographic guide is positioned over the occlusal surfaces of the neighbouring teeth. Metallic cylinders will be used by a sleeve to guide the drills. In two cadavers an anchor pin was planned.

3D Accuitomo® set-up

Data were acquired through the flat panel 3D Accuitomo FPD® cone-beam CT (J. Morita, Kyoto, Japan) at the department of Radiology at the University of Leipzig. The first scan was taken while the partial edentulous mandible was positioned wearing the scan template. The exposure parameter settings selected included: 80 kV and 4 mA. A second scanning of the template alone was also required (Verstreken et al. 1996). The scanning parameters were then lowered to 60 kV and 1 mA to allow visibility of the template. The exposure time was 17.5 s and a 360° turn was selected.

The image reconstruction took approximately 3 min. and the distance between the images was 0.5 mm. The radiographic area was 60 mm in height and 60 mm in diameter (voxel size: 0.125 mm × 0.125 mm × 0.125 mm). Six gutta-percha points, serving as radio-opaque fiducials, allow visualization of the template using the dual-scanning technique (Verstreken et al. 1996).

3D planning software

Images were reconstructed from the projection data with a personal computer (Dell workstation, PWS360 Intel®, Pentium® 4 CPU 2.80 GHz, 1.00 GB of RAM, Dell Co., CA, USA). The data

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acquired were saved on a local server and then sent to the hospital PACS imaging server Impax® (Agfa Medical Systems, Mortsel, Belgium) for storage and easy access. All images originally stored in DICOM format were converted to a format that could be read by the pre-processing software of Procera® (Medicim) to enable pre-operative implant planning. In this software, fusion of both images – that of the specimen wearing the prosthesis, and that of the prosthesis alone – is performed. This was accomplished on the basis of radio-opaque markers, which allowed easy discrimination in both images. Once implant positions were selected, the virtual prosthesis could be integrated into the image (Fig. 2). This allowed modification and adjustment for final implant placement, taking into consideration the planned prosthesis. Both plannings were made using the software for planning in the 2D/3D environment, to integrate all the demands for a proper placement of implants (biomechanical, bone anatomy, prosthetic teeth). The slice viewer displayed 2D re-slices in all planes.

Once interactive implant planning has been performed, it must be transferred in a precise manner to the operative field. A computer-based transfer could be performed with stereolithographic drill guides (Verstreken et al. 1996, van Steenberghe et al. 2002). Therefore, the completed image data set was sent electronically to the manufacturing facility (Nobel Biocare AB) for the splint construction (Fig. 3). A CAD/CAM program Procera® (Nobel Biocare AB) used the radiographic guide and the 3D information of the planned drill paths to design the drill guide. The drill guide was then produced by stereolithography (van Steenberghe et al. 2003). Its special design consisted of a resin (USP Class 6 approved) backbone with cylindrical openings into which stainless-steel tubes can be fitted. Once this phase of the process was completed, the surgical splint was positioned on the remaining teeth and implant insertion into the bone could be performed.

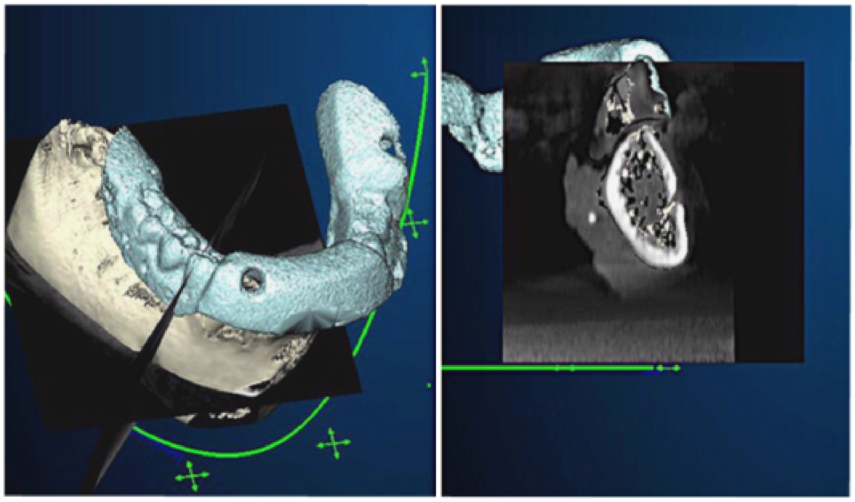

Fig. 2. Planning software. On the left part of the split screen a fully 3D view is shown, while on the right side a two dimensional view of the respective slide is shown. A reshaped curve guides the reslice along the arch of the jawbone. The axis of the implant is positioned based on prosthetic and anatomic demands.

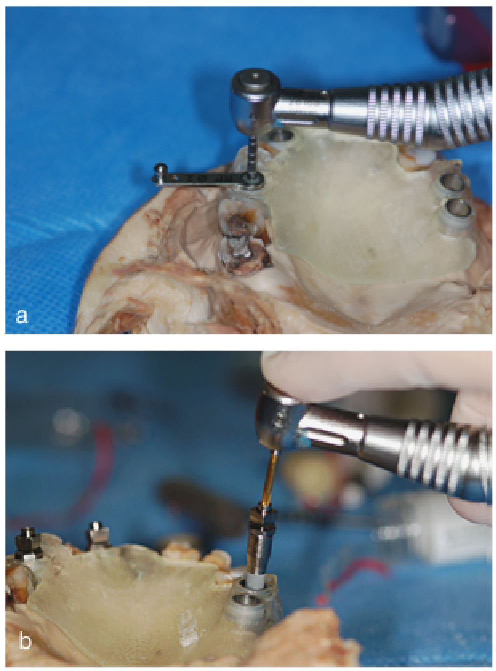

Fig. 3. Surgical setup. (a) The bur, with the horizontal indications for depth control, is guided while preparing the cavity. (b) To insert the implant, no extra guide is used, it is guided by the cylinder in the surgical template.

Surgical protocol

For four cadavers, 12 implants were planned. The implants used in this technique were roughened surface Ti-Unite™ Brånemark system® implants (Nobel Biocare AB) of a self-tapping design. They were placed to a specific depth, limited by the vertical stop on the fixture mount. The diameter and length used in each pre-determined implant site are shown in Table 1.

Validation of the technique

Post-operatively, a CBCT scan, taken by the same 3D Accuitomo FPD® (J. Morita), was undertaken to check the position of the implants. The settings were the same as those used pre-operatively: 80 kV and 4 mA. The post-operative data were matched with the pre-operative images using the fusion criterion of multi-modality image registration (Maes et al. 1997) (Fig. 4). The post-operative cone-beam images are geometrically aligned with the planning images by automated image registration using maximization of mutual information. Each anatomical location is mapped to its corresponding location.

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Table 1. Overview of the implants placed in different jaws, and the results of matching procedure

Jaw	Position implant	Length implant (mm)	Diameter implant (mm)	Position pin	Deviation hex (mm)	Deviation tip (mm)	Angulation (°)
1 Upper jaw	14	13	4		0.3	0.7	1.8
	12	15	4		0.8	1	2
	23	15	4		2	2.4	1.8
	24	10	4		1.7	1.6	0.7
2 Lower jaw	35	11.5	3.75		0.5	0.6	0.9
	37	10	3.75		1.3	1.5	4
3 Lower jaw	34	13	3.75		0.4	0.3	2.1
	36	13	4	36–37	0.3	0.5	1.5
	37	11.5	4		0.7	0.9	1.8
4 Lower jaw	44	13	3.75		1.2	0.8	2.4
	45	13	4		1.5	1.5	1.7
	46	11.5	4	47	2.3	2.4	1.4
Mean					1.1	1.2	1.8
Standard deviation					0.7	0.7	0.8
Range					0.3–2.3	0.3–2.4	0.7–4

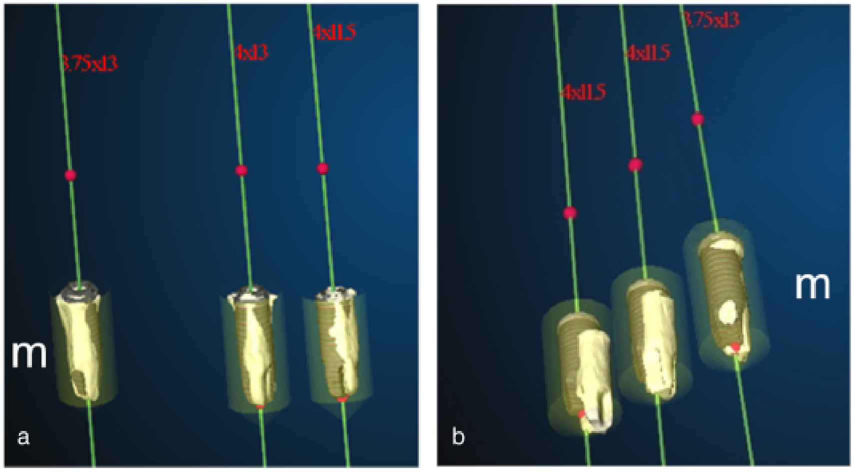

Fig. 4. Lateral view of matching of pre- and post-surgical images. The yellow halo is the safety zone available in the planning, and the white structure represents the deviation of the implant towards the planning. Light grey represents the deviation of surgery data (m = mesial). (a) Matching result for cadaver 3. (b) Lateral view for cadaver 4 showing bending effect of free ending surgical template, with a mesio-distal component responsible for the linear deviation.

Results

The surgical procedure was performed uneventfully. The differences between the actual position of each implant and its position in the planning were analysed (Table 1).

The deviation at the entrance point ranged between 0.3 and 2.3 mm, with a mean of 1.1. Comparing the deviation at the tip of the implant, the length of the implant had to be taken into account. The deviation ranged between 0.3 and 2.4 mm. The highest values (2.5 mm) were found for two implants with a length of 15 and 11.5 mm. Only one out of 12 implants had a deviation beyond 2.5°. The mean angular deviation was 1.8°.

In general, deviations were larger if the splint had no support over the full dental arch. Implants with neighbouring support of a tooth most often showed smaller deviations than distal implants, placed using a free-ending template, lacking dental support for the upper jaw, where the teeth were not fully covered by the template but where the latter was only stabilized by the palate.

Discussion

The present ex vivo pilot study demonstrates the ability of cone-beam CT images to offer a reliability data set for planning and further transfer of oral implant placement in partial edentulism. The study also indicates that the results can be improved by considering the various crucial points such as template fit and template stability.

The study documents various deviations that may occur in the transfer phase, but the fact that the 3D computer-based planning and transfer resulted in an almost perfect match in one specimen, proved that the present technique offers potentials for clinical application. One crucial factor is surely the stability and inherent support of the template. This is far more difficult to accomplish in partial than full edentulism. Unfortunately, studies are lacking, but several reasons can be assumed. In partial edentulism, the template is supported by two different surfaces; stiff (teeth) and soft (mucosa). The aim of a good template is to be rigid and stable in only one position. When the accuracy is (too) optimal or very less micro-roughness (perhaps due to the stereolithographic procedure) is present, stiff surfaces will not permit a stable fit. However, in edentulous jaws, this indulgency could be expected from soft tissues. The degree of freedom in edentulous patients is higher, although not assuming a more accurate positioning. Furthermore, it may also be hypothesized that bending of the template might have occurred, although the template normally has to fracture when very large forces are applied. Once the template is positioned, one or more anchor pin(s) through the alveolar process could help to provide more support. Instead of full edentulism, the availability to place anchor pins is reduced in partially edentulous jaws. Furthermore, and in general, any reduction in technical complexity may diminish the potential errors and inaccuracies. Previous studies on the accuracy of the transfer to the surgical field, van Steenberghe et al. (2002) and Sarment et al. (2003), reported maximum deviations of 1.1 and 1.6 mm, respectively, between planned and actual locations in the longitudinal direction of the implants. The maximal angular deviations were 3.8° and 5.4°. It should be pointed out, however, that the former study was clinical but with the surgical guide bone supported and the latter was in vitro. They both used CT scan-derived drill guides with sleeves matching the drill diameters inserted into the holes in the guide.

In this experimental set-up, cadaver specimens were used to mimic the in vivo situation. Still, the bone of cadavers

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should be considered as more brittle and less resistant, not allowing a full extrapolation to clinical practice. Furthermore, the soft tissue compressibility is less flexible, leading to less stability such as in distal areas without anchor pins. The present pilot data show that for free-ending situations, the linear deviation is caused by a difference in the mesio-distal direction between planning and surgery as seen in cadaver 4 (Fig. 4b). It may be assumed that a bending effect of the template, and the flexibility of the soft tissues could be responsible for the deviations and for an improper fit.

Di Giacomo et al. (2005) measured the deviation between planning and surgery in vivo. Radiographic data were obtained by CT, and for each twist drill diameter (# = 3) a surgical guide was manufactured. On average, the match between the planned and the placed implants was within $7.25^\circ \pm 2.67^\circ$, implant shoulder 1.45 ± 1.42 and 2.99 ± 1.77 mm at the implant axis. Large deviations (2.6 and 3.0 mm at the apex with an angular deviation of 10° and 12.2°) were found in specimens without a proper fit from the surgical template. The angular deviations, reported in the present study, appear to be much smaller, thus implying an improved clinical accuracy.

Because the use of cone-beam CT for pre-operative planning of implant placement has become a widely accepted imaging modality (Araki et al. 2004, Guerrero et al. 2006, Loubele et al. 2006) to gain in image quality, while at the same time costs and radiation doses are substantially reduced, cone-beam devices will be used more and more. Several studies have demonstrated that linear measurements on cone-beam CT images are accurate for dentomaxillofacial use (Mozzo et al. 1998, Lascala et al. 2004). The data set of the present research consisted of 3D Accuitomo FPD® (J. Morita) images, which were segmented and used for a reliable 3D bone surface model.

One should also consider the present findings in the light of alternative transfer techniques. Fortin et al. (2000) invented a specially designed mechanical tool to transfer the pre-operative implant axis from the planning to a surgical template by a numerically controlled drilling machine. Results based on cone-beam CT imaging coupled with the image-guiding system revealed high precision for the transfer through a robot drilling machine: 0.2 mm translation, and $<1.1^\circ$ for rotation on three master models (Fortin et al. 2002). The shortcoming of a misfit of a drill guide is not present in navigation surgery, where anatomical landmarks are continuously matched. Several studies showed this precision; the overall accuracy is 0.96 ± 0.72 mm (for a review, see Widmann & Bale 2006), with a maximum error of 3.5 mm (Birkfellner et al. 2001, Wanschitz et al. 2002, Wagner et al. 2003). The deviation in angulation scores is sometimes large during navigation (10.4° Wanschitz et al. 2002). Navigation systems are not easy to use, because the surgeon has to integrate the technological constraints during the surgical procedures. Feducial markers must be detected continuously by the external sensor. One can question its actual applicability during oral surgery under local anaesthesia.

There is no consensus about the precision needed for an acceptable precision of an image-based transfer to surgery. What really matters is the worst-case scenario where all deviations add up in the same direction. Indeed, this may potentially occur and cause damage to some anatomical structures.

The present data indicated that more research is needed before partially edentulous implant cases can be transferred from cone-beam CT image-based planning to the surgical field with stereolithography. One should try to avoid any potential deviation by providing an answer to the various causal factors of the errors. Development of a fully stabilized template design with a perfect fit is surely one of the key factors for success. Further clinical studies, using a greater number of partially edentulous sites and elaborate template design, should be performed to evaluate the reliability, validity and global applicability of stereolithographic surgical guides for any kind of implant therapy and based on any kind of 3D-based image data. The continuous and rapid development of new cone-beam CT imaging techniques will undoubtedly necessitate a continued scientific assessment of the potentials of 3D image-based planning and transfer for oral implant placement.

Conclusions

Flat panel cone-beam CT images may be useful for computer-aided rapid prototyping of surgical guides for partial edentulism. Further research is needed to optimize the set-up and template design in all cases, as such, to further reduce linear and angular deviations of the transfer technique.

Ex vivo research, with a larger number of samples, and in vivo results should be performed to validate the accuracy and real impact of the stereolithographic guide.

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Clinical Relevance

Scientific rationale for the study: Considering the variable anatomy of edentulous jaw bones, 3D image-based planning and transfer offer clinicians a more reliable and efficient surgical outcome.

Principal findings: Based on these results, we have to take into account a maximum deviation of 2.4 mm (mean = 1.2 mm) at the apex of the implant, when using this protocol to transfer a pre-operative planning via a drill guide to the surgical field.

Practical implications: The use of cone-beam CT with all its advantages can thus be recommended for image acquisition in partial edentulism.

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